Condensed-matter physics: Catching relativistic electrons

Citation
Zhu, Zhihuai, and Jennifer E. Hoffman. 2014. "Condensed-Matter Physics: Catching Relativistic Electrons." Nature 513 (7518) (September 17): 319–320. doi:10.1038/513319a.

Published Version
doi:10.1038/513319a

Catching relativistic electrons

Recent experiments found that low-energy electrons mimic relativistic high-energy particles in cadmium arsenic. This defines the first stable '3D Dirac semimetal', which holds promise for fundamental physics and practical applications.

Zhihuai Zhu & Jennifer E. Hoffman

In classical Newtonian mechanics, an object's energy varies as the square of its velocity or momentum (Fig. 1a) — a rule that drivers should treat with respect. Photons, neutrinos and other light, fast-moving particles are governed instead by Einstein's theory of relativity: their energy scales linearly with their momentum, with fixed velocity equal to the slope. Such relativistic high-energy particles hold the keys to fundamental understanding of our Universe. But where do electrons — which determine the more practical properties of the materials immediately around us — fit into this picture? Electrons move very fast but their motion is not primarily relativistic in conventional solids. However, in a paper published in *Physical Review Letters*, Borisenko *et al.*[1] report the discovery of relativistic motion of low-energy electrons in cadmium arsenic (Cd_3As_2). Taken together with similar findings described in three independent papers, by Neupane *et al.*[2], Liu *et al.*[3] and Jeon *et al.*[4], this result paves the way for future relativistic electronics.

The realization of low-energy electrons mimicking high-energy relativistic particles began a decade ago with the isolation of two-dimensional (2D) carbon in the form of graphene[5], whose dual significance for the exploration of fundamental physics and for revolutionary applications has prompted over 100,000 publications, 7,000 patents and a 2010 Nobel Prize. Electrons in graphene are described as massless Dirac fermions, because they have half-integer spin, which makes them fermions, and their linear energy–momentum relation obeys Dirac's famous wave equation that first united quantum mechanics and special relativity almost a century ago. Graphene is also a semimetal, meaning that its Fermi energy (the dividing line between filled and empty electronic states) sits ideally at its 'Dirac point' where its valence and conduction energy bands meet (Fig. 1b), and may be easily tuned with applied voltage. The resultant electron or 'hole' (the absence of an electron) charge carriers have high mobility — a measure of inverse electrical resistivity per carrier, which increases with carrier velocity but decreases with carrier scattering.

Graphene's moderately high carrier velocity of about 10^5 metres per second, combined with the reduced intrinsic scattering possibilities due to the small carrier density inherent to a Dirac semimetal, can give a mobility up to 140 times that of silicon — the material of choice for most electronic applications. Therefore, graphene offers promise for making novel high efficiency electronic devices. However, graphene is challenging to fabricate and manipulate in large areas, and its mobility is extremely susceptible to scattering from environmental defects because graphene is *all* surface.

A second kind of 2D Dirac semimetal arises from another relativistic effect of electrons, spin–orbit coupling — the interaction between an electron's spin (a tiny magnetic moment associated with each electron) and the induced magnetic field from the electron's orbital motion. Spin–orbit coupling is generally small for materials made up of light atoms such as carbon, but for materials containing heavy atoms like bismuth and cadmium, the interaction can be significant; for example it can invert the valence and conduction bands in the bulk of an insulator. The inversion can lead to topologically protected surface Dirac fermions — surface carriers that are robust against some local disorder and have their spin locked to their momentum (that is, the carrier's momentum determines its spin). These so-called topological insulators[6,7] provoked tremendous excitement about possible applications such as low-energy-loss spintronic devices, which manipulate the spin rather than the charge of electrons, for high-performance computing. But despite their name, existing topological insulators have excess conducting bulk electrons which overwhelm the surface Dirac fermions and foil their use.

Meanwhile, new ideas were brewing, suggesting that 3D Dirac semimetallic states could exist in the bulk of a solid material. It was known that such states could occur under finely tuned conditions, such as the exact concentration of bismuth at which spin–orbit coupling becomes strong enough to invert the bulk energy bands in $Sb_{1-x}Bi_x$. But more recent theoretical work predicted their robust occurrence in pure materials with certain crystalline symmetries: first unstable BiO_2 (ref. 8), then air-sensitive Na_3Bi (ref. 9), and finally the stable compound Cd_3As_2 (ref. 10). Furthermore, when time-reversal or spatial-inversion symmetries are broken, for example by application of magnetic field or pressure, each Dirac point can split into two copies, where the electrons become Weyl fermions[11] — fermions that have opposite chirality (spin orientation with respect to their direction of motion). Such Weyl fermions could enable robust spintronics in three dimensions.

Cd_3As_2 has been known for 40 years for its extraordinary carrier mobility — it is larger than suspended graphene and is the highest of any bulk material. Thanks to the recent studies by Borisenko *et al.*[1], Neupane *et al.*[2] and Liu *et al.*[3] — who conducted experiments on Cd_3As_2 using a technique called angle-resolved photoemission spectroscopy (ARPES) — we now understand that the high mobility arises from high-velocity 3D Dirac semimetal states.

During ARPES experiments, monochromatic light is incident on a sample and electrons can absorb a photon and escape from the material. To unveil the full 3D energy–momentum relation of electrons within Cd_3As_2, a challenging but crucial step was to precisely measure the energy and momentum of emitted electrons while tuning the photon energy through a wide range. The data[1–3] clearly show a linear energy–momentum relationship, with two Dirac points along a crystal axis of four-fold rotational symmetry (Fig.1c). This result proves that electrons in this material are 3D massless Dirac fermions as predicted[10]. Measurement of the energy–momentum slope gives electron velocity as high as about 10^6 m s^{-1} (ref. 2), but with a tenfold discrepancy between the three studies[1–3], which could be due to differences in sample quality or the angle of the exposed surface. Liu *et al.* additionally demonstrated that the carrier concentration in Cd_3As_2 could be finely tuned by 'doping' the surface of the material with potassium atoms[3], making it a flexible platform for future studies.

Most recently, a study by Jeon *et al.*[4] used a scanning tunnelling microscope to confirm Cd_3As_2 as a 3D Dirac semimetal down to atomic length scales, and to visualize how dopant atoms scatter primarily carriers in the valence band, preserving the mobility of carriers in the high-velocity conduction band[4]. Furthermore, Jeon and colleagues applied a magnetic field, which is not possible in an ARPES setup. Although the field breaks time-reversal symmetry which would be necessary to split the Dirac fermions into the more exotic chiral Weyl fermions, its orientation in this experiment also breaks the four-fold rotational symmetry of the crystal which was necessary to realize the Dirac fermions in the first place, so the first glimpse of Weyl fermions will need to wait for a follow-up experiment in which the magnetic field has a different orientation.

The work on Cd_3As_2 (refs 1–4), together with the lower mobility Na_3Bi reported earlier this year[12], confirm the existence of relativistic Dirac fermion motion inside 3D materials. Despite its exciting new physics, the application potential of Cd_3As_2 is limited by its small band inversion energy — the relativistic nature is not robust at room temperature[4]. Furthermore, Cd_3As_2 is not exactly something you want in your drinking water. Nevertheless, given the new understanding that robust Dirac fermions can arise in solids from general crystalline symmetries and strong spin–orbit coupling, there are likely numerous 3D Dirac semimetals yet to be discovered[8]. Immediate priorities include magnetic-field and pressure control to isolate chiral Weyl fermions in existing materials, realization of these materials as thin films to access a phenomenon known as the quantum spin Hall effect to visualize the spatial flow of surface Dirac fermions[13], and computational modelling to predict new materials and heterostructures with larger band inversion energy[14]. Then exotic applications such as a 'chiral battery', or a 'quantum amplifier' of magnetic field, may be on the horizon[15].

Zhihuai Zhu *and* **Jennifer E. Hoffman** *are in the Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA.*

e-mails: zhzhu@physics.harvard.edu; jhoffman@physics.harvard.edu

1. Borisenko, S. *et al. Phys. Rev. Lett.* **113,** 027603 (2014).
2. Neupane, M. *et al. Nature Commun.* **5,** 3786 (2014).
3. Liu, Z. K. *et al. Nature Mater.* **13,** 677–681 (2014).
4. Jeon, S. *et al. Nature Mater.* doi:10.1038/nmat4023 (2014).
5. Geim, A. K. & Novoselov, K. S. *Nature Mater.* **6,** 183–191 (2007).
6. Hasan, M. Z. & Kane, C. L. *Rev. Mod. Phys.* **82,** 3045–3067 (2010).
7. Qi, X.-L. & Zhang, S.-C. *Rev. Mod. Phys.* **83,** 1057–1110 (2011).
8. Young, S. M. *et al. Phys. Rev. Lett.* **108,** 140405 (2012).
9. Wang, Z. *et al. Phys. Rev. B* **85,** 195320 (2012).
10. Wang, Z. *et al. Phys. Rev. B* **88,** 125427 (2013).
11. Wan, X. *et al. Phys. Rev. B* **83,** 205101 (2011).
12. Liu, Z. K. *et al. Science* **343,** 864–867 (2014).
13. Kane, C. L. & Mele, E. J. *Phys. Rev. Lett.* **95,** 226801 (2005).
14. Burkov, A. A. & Balents, L. *Phys. Rev. Lett.* **107,** 127205 (2011).
15. Kharzeev, D. E. & Yee, H.-U. *Phys. Rev. B* **88,** 115119 (2013).

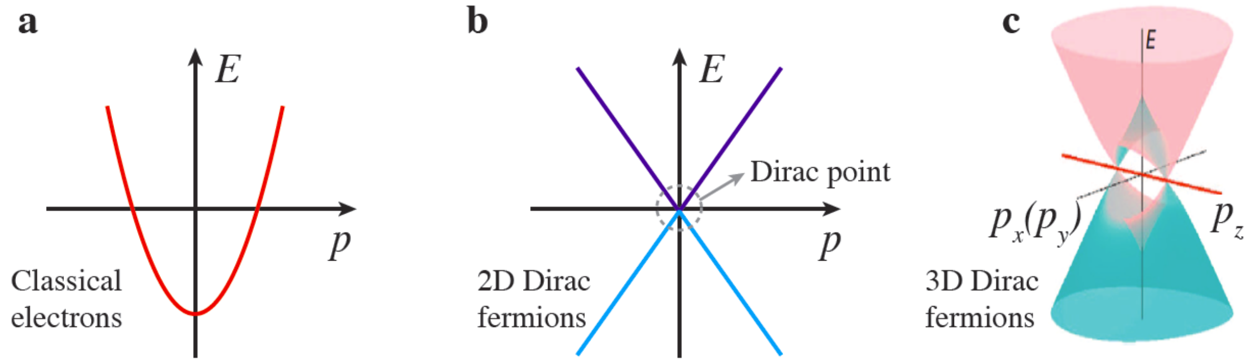

Figure 1 | Energy–momentum spectrum of electrons. a, Classical electrons exhibit a parabolic relationship between their energy (E) and momentum (p). **b**, Two-dimensional (2D) Dirac fermions, such as electrons in graphene, have valence (cyan) and conduction (blue) energy bands, with a linear energy–momentum relationship, that touch at a point called the Dirac point in the 3D space formed by E, p_x and p_y. Shown here is a 2D cut of the 3D space. **c**, A 3D cut of the 4D (E, p_x, p_y, p_z) energy–momentum relationship of 3D Dirac fermions such as those discovered[1–4] in Cd_3As_2, with two Dirac points along a special high-symmetry axis (p_z).